U.S. DEPARTMENT OF ENERGY | Nuclear Energy

Fuel Cycle Research and Development

Advanced Nuclear Fuels

Jon Carmack
Deputy National Technical Director

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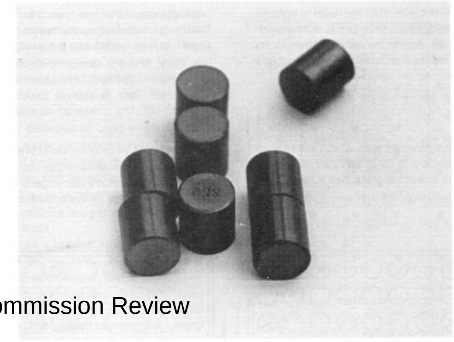
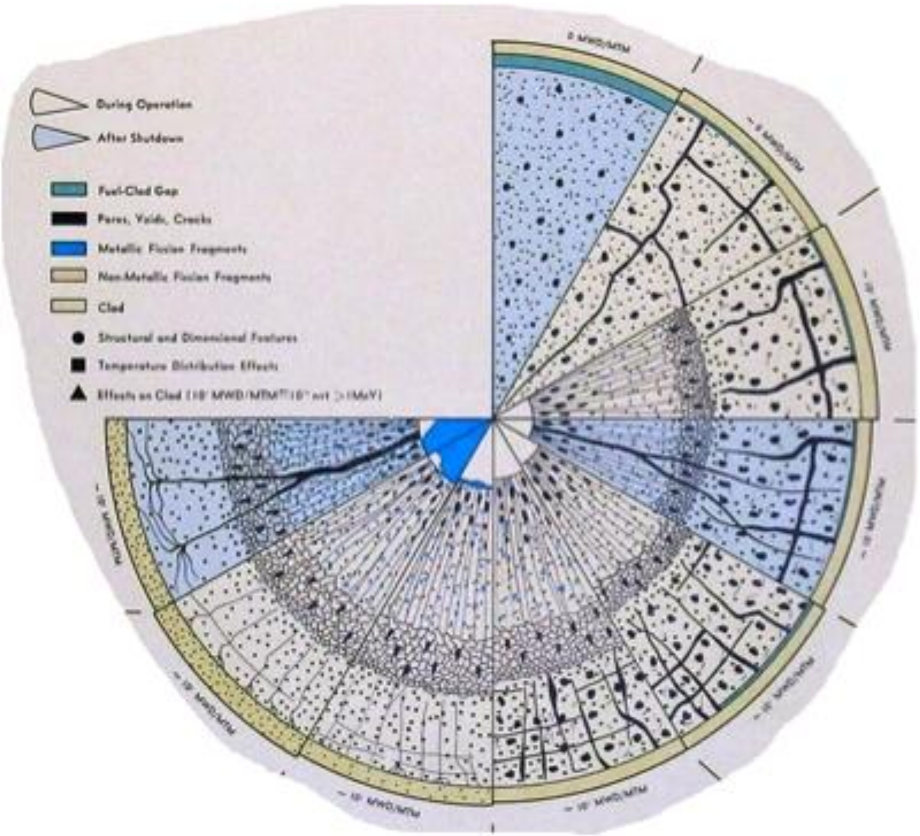
Presentation Outline

- **Why is fuel important?**
- **Nuclear Fuel Development**
  - Empirical Approach
  - Goal-oriented science based approach
  - Dual-track approach
  - Transformational Solutions
- **Where we have come from and where we are going.**



Why is nuclear fuel important?

Oxide fast reactor fuel cross-section



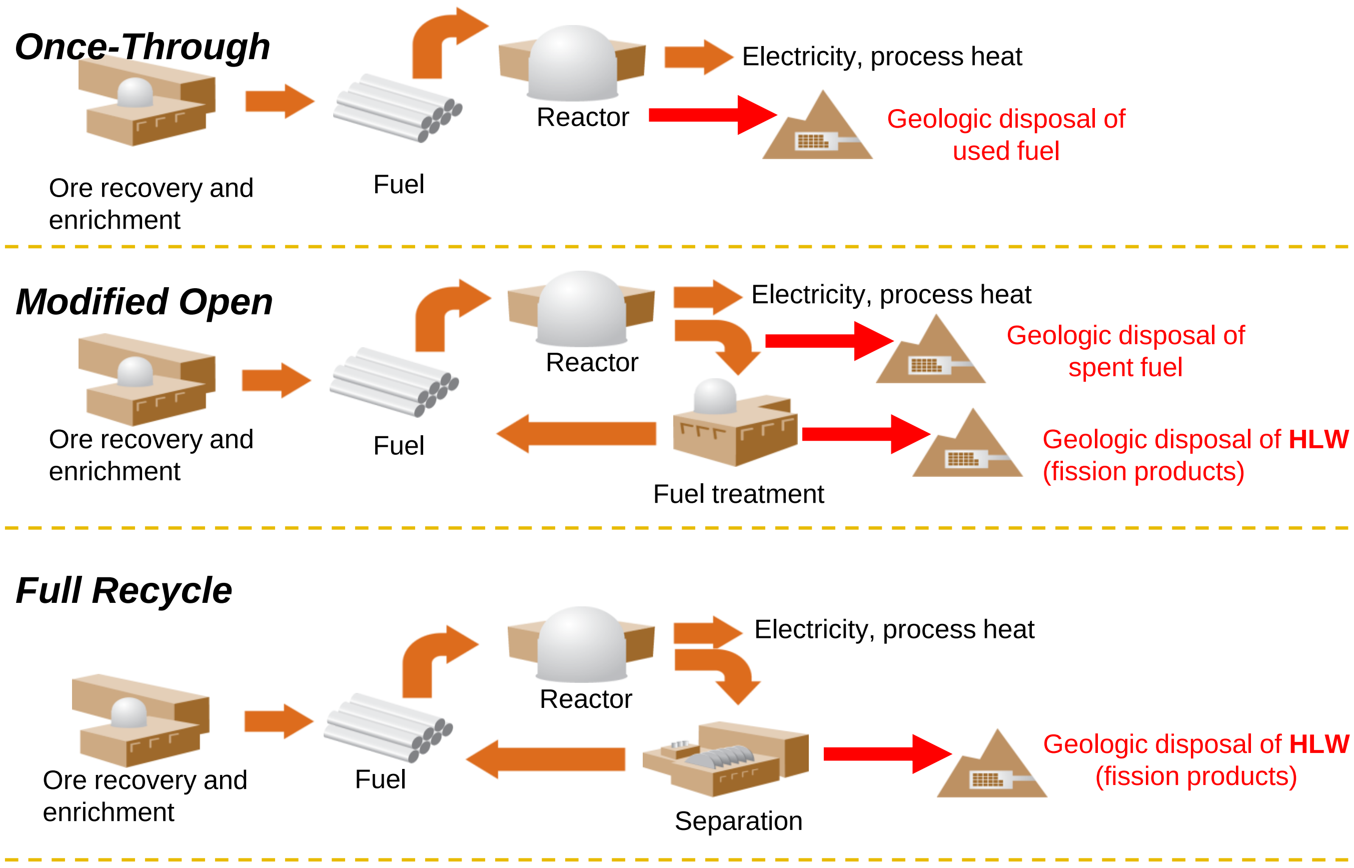
- **Changes dramatically with time.**
- **Performs at very high temperatures.**
- **Must have high reliability.**

Fuel is a complex material system undergoing massive changes during its lifetime.

- **Longer cycle length requires higher enrichment.**
- **Higher reactor power requires higher power fuels.**
- **Destroying fission products requires transmutation fuel compositions.**

Fuel Development is a long and extensive process (15 to 20 years) and is the critical path to deployment of advanced technologies.

Three Fuel Cycle Strategies



Note: Interim storage will be required for all options

Advanced Fuels Campaign Mission & Objectives

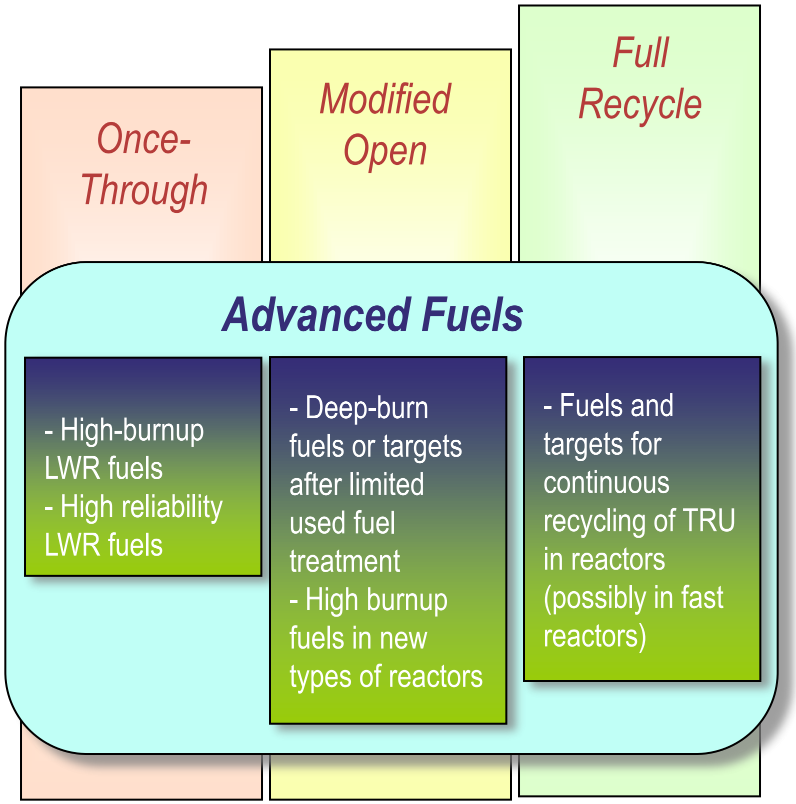
- **Mission**

  Develop and demonstrate fabrication processes and in-pile performance of advanced fuels/targets (including the cladding) to support the different fuel cycle options defined in the NE roadmap.

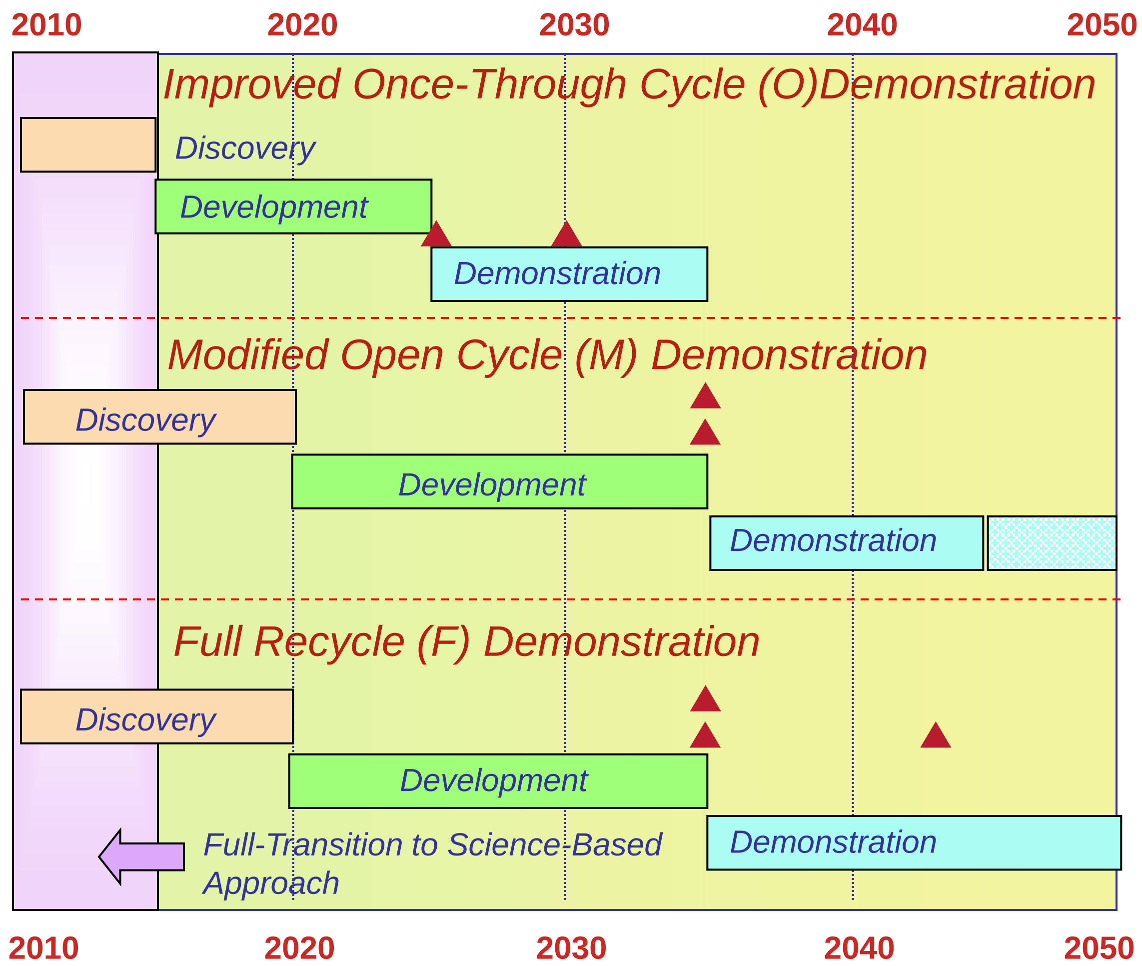
- **Objectives**

  Development of the fuels/targets that
  - Increases the efficiency of nuclear energy production
  - Maximize the utilization of natural resources (Uranium, Thorium)
  - Minimizes generation of high-level nuclear waste (spent fuel)
  - Minimize the risk of nuclear proliferation

- **Grand Challenges**
  - Multi-fold increase in fuel burnup over the currently known technologies
  - Multi-fold decrease in fabrication losses with highly efficient predictable and repeatable processes



Objective 3: High-Level Schedule



What have we done?
Base Fast Reactor Fuel Technology: US Experience (1960s to 1996)

	Metallic	Mixed Oxide	Mixed Carbide
Driver Fuel Operation	≥ 120,000 U-Fs rods in 304LSS/316SS 1-8 at.% bu ~13,000 U-Zr rods in 316SS 10 at.% bu	>48,000 MOX rods in 316SS (Series I&II) 8 at.% bu;	None applicable
Through Qualification	U-Zr in 316SS, D9, HT9 ≥ 10at.% bu in EBR-II & FFTF	MOX in HT9 to 15-20 at.% bu (CDE) MOX in 316SS to 10 at.% bu	None applicable
Burnup Capability & Experiments	600 U-Pu-Zr rods; D9 & HT9 to > 10 - 19 at.% in EBR-II & FFTF	4300 MOX rods in 316SS to 10 at.%; fab var's; CL melt 3000 MOX rods in EBR-II; peak at 17.5at.% bu 2377 MOX rods in D9 to 10-12 at.% bu; some at 19 at.% bu	18 EBR-II tests with 472 rods in 316SS cladding; 10 rods up to 20 at.% w/o breach 5 of which experienced 15% TOP at 12 at.% 219 rods in FFTF, incl 91 in D9, 91 with pellet & sphere-pac fuel
Safety & Operability	6 RBCB tests U-Fs & U-Pu-Zr/U-Zr(5) 6 TREAT tests U-Fs in 316SS (9rods) & U-Zr/U-Pu-Zr in D9/HT9 (6 rods)	18 RBCB tests; 30 breached rods 4 slow ramp tests 9 TREAT tests MOX in 316SS (14 rods) & HT9 (5 rods)	10 TREAT tests (10 rods; Na or He bond); ≤ 3-6 times TOP margins to breach Loss-of-Na bond test; RBCB for 100 EFPD; Centerline melting test

Crawford, Porter, Hayes, Journal of Nuclear Materials, 371: 202-231 (2007).

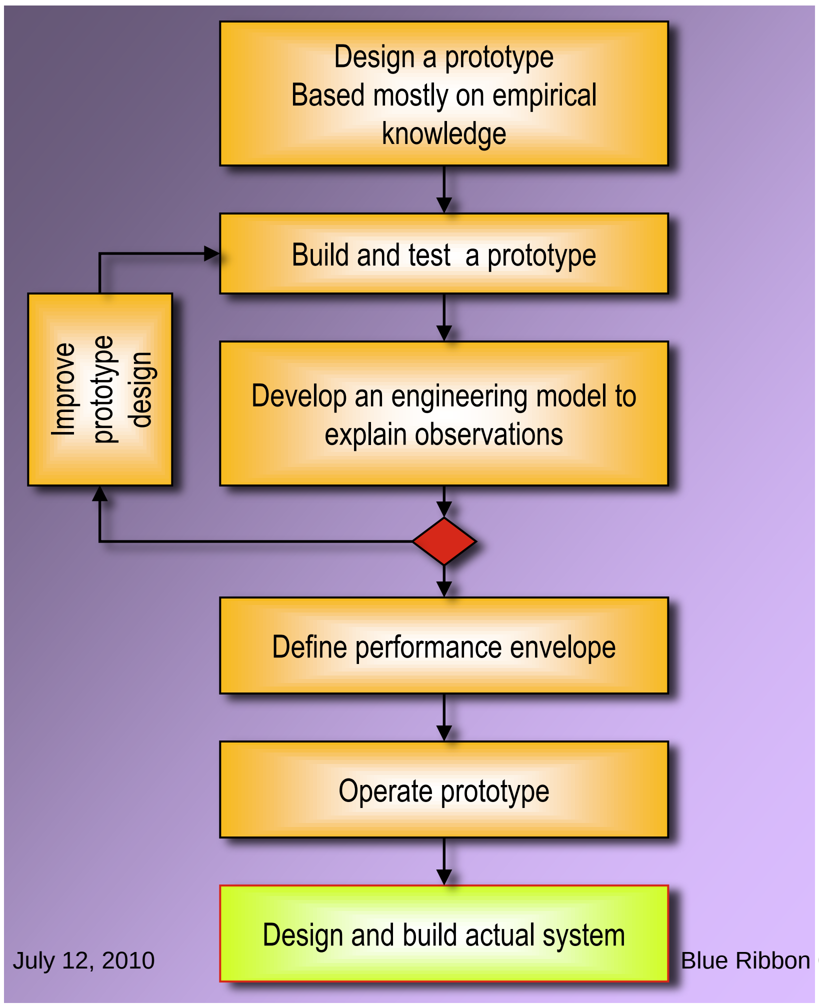
Post-1996 IFR* Transmutation Fuel Development in the U.S

*IFR: Integral Fast Reactor

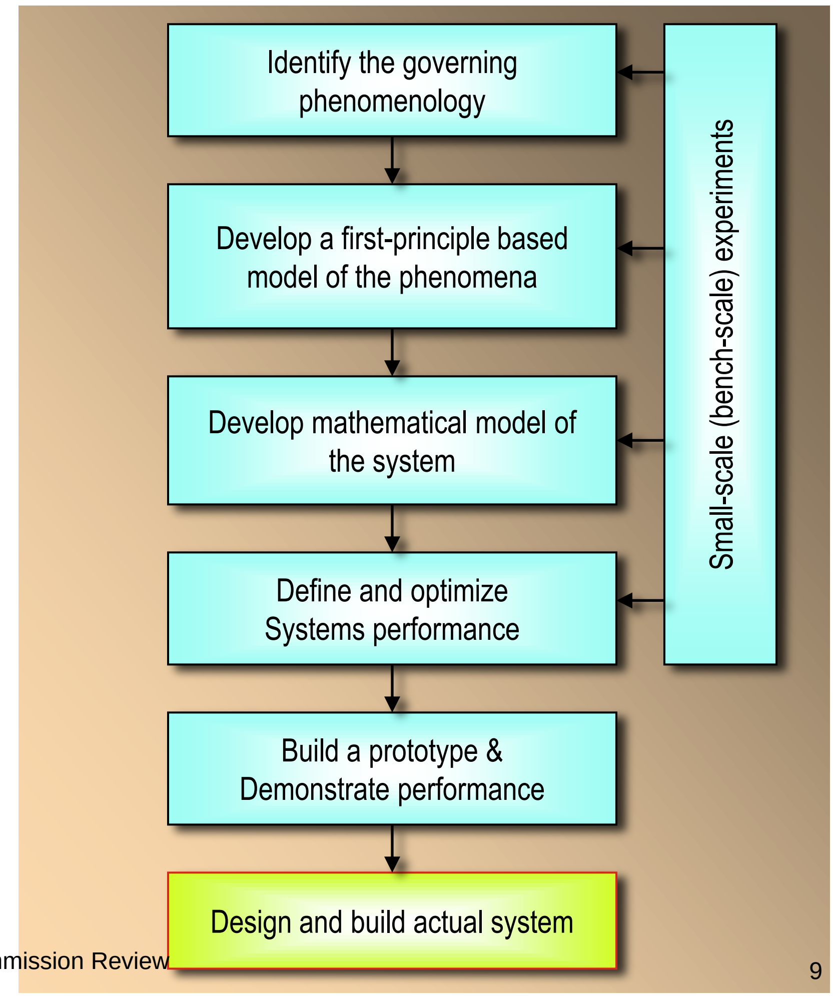
- **ATW & AAA (1999-2003)**
  - Metal and nitride fertile-free fuel development for fast spectrum ADS
  - European ADS program's focus on fertile-free oxide fuels
  - Relatively small budgets
- **AFCI (Pre-GNEP) (2003-2006)**
  - Continuation of metal and nitride fertile fuels for fast reactors
  - Initial work on carbide-based dispersion fuels for GFRs
  - Initial work on transmutation fuels for LWRs
    - *TRU-MOX*
    - *Inert Matrix Fuels (IMF)*
  - TRISO Fuel in support of VHTR efforts
    - *A short duration activity on TRISO fuels with TRU*
- **AFCI (GNEP) (2006-209)**
  - Focus on metal and oxide sodium-cooled fast reactor fuels (full TRU recycling)
  - Considerations for MA targets (heterogeneous recycling)
- **FCRD (Started in 2010)**

Prototype-Based vs. Science-Based Approaches

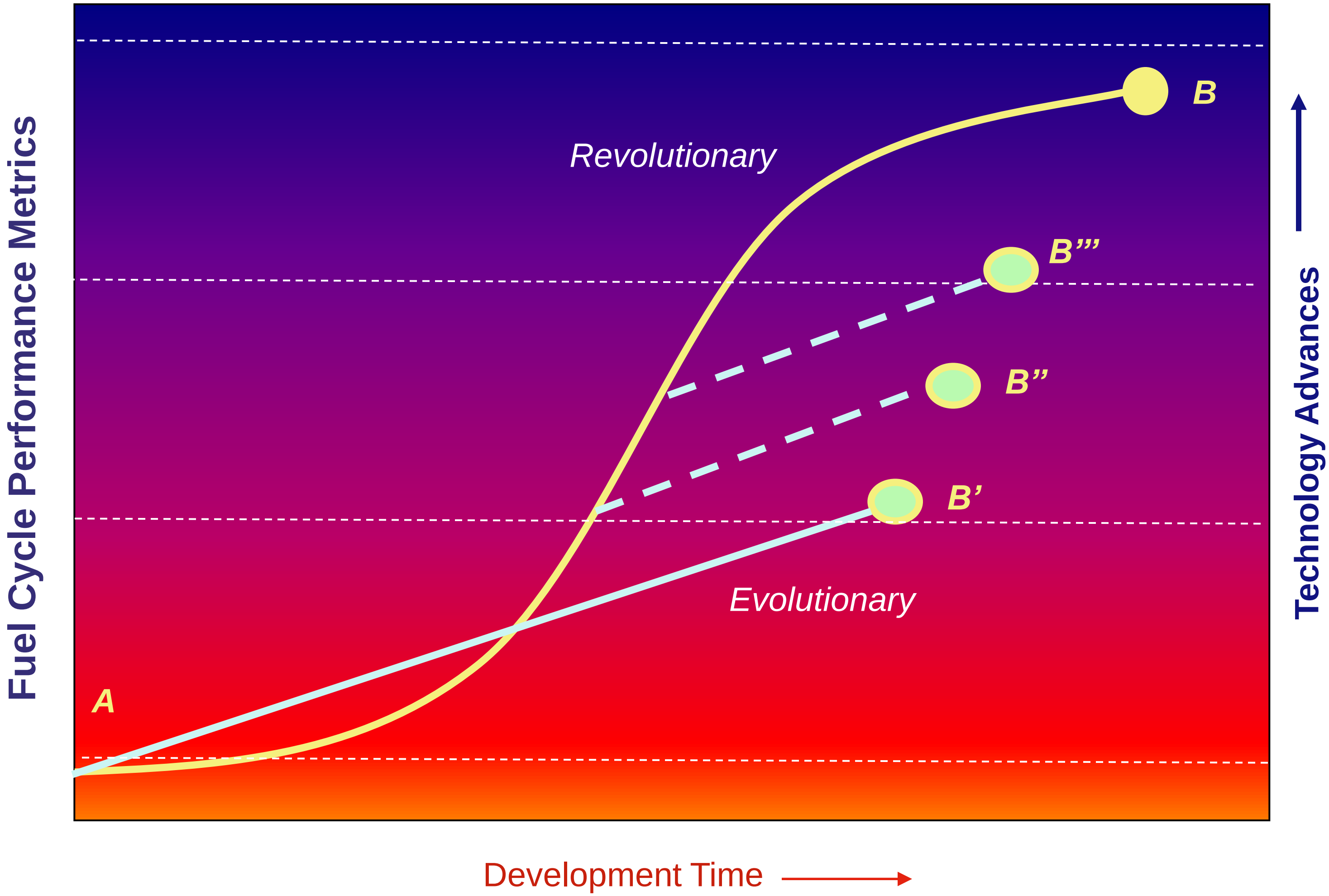
Prototype Dominated Approach
Empirical - Observational



"Goal Oriented Science-Based" Approach - Predictive



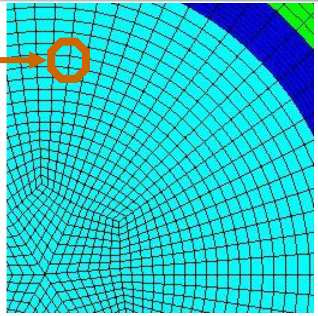
Technology Development - Dual-Track Approach

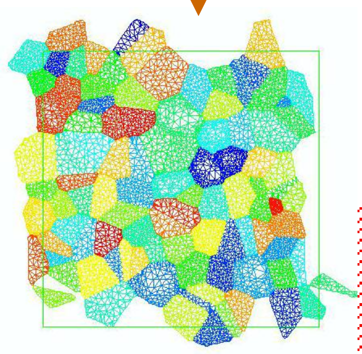


Advanced Nuclear Fuel is the gateway technology needing transformational solutions

- **Encourage Innovative Ideas & Innovative Solutions**
  - Transformational fuel/target concepts
  - Transformational fabrication process concepts
  - New testing concepts - faster, more insightful
  - Novel instrumentation
    - *In-pile*
    - *Characterization*
- **Often the process inspires innovative, transformational ideas**
  - Innovation will accelerate once the tools needed to implement the science-based approach are in place
  - Incubation period
- **The goal is to avoid killing innovative ideas prematurely without expending limited resources on impractical concepts**
  - Continuous evaluation and screening based on objective criteria
  - Collaboration with systems engineering team

Our goal oriented science based approach emphasizes meso-scale understanding of fuels behavior.





Continuum Mechanics (IPSC)

Scale bridging

Numerical Solution Of Unified Mesoscale Model
- 3d solution of phase-field and FEM equations

Unified Mesoscale Model
Combined phase-field & transport theory

Theory
Comprehensive crystal phase-field (Cahn-Hilliard & Allen-Cahn) equations.

Experiments
Characterization of microstructure formation & evolution, measurements of crystal properties

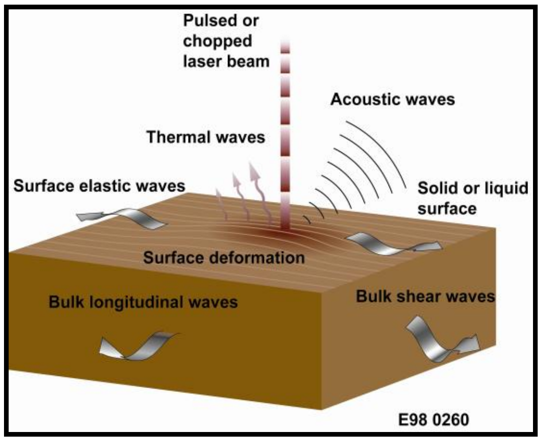
Scale bridging

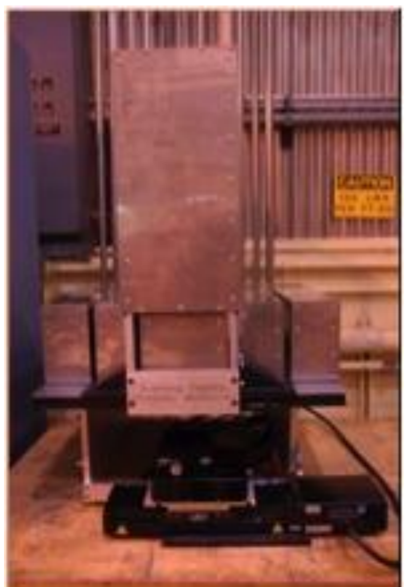
Electronic Structure, Molecular Dynamics, KMC

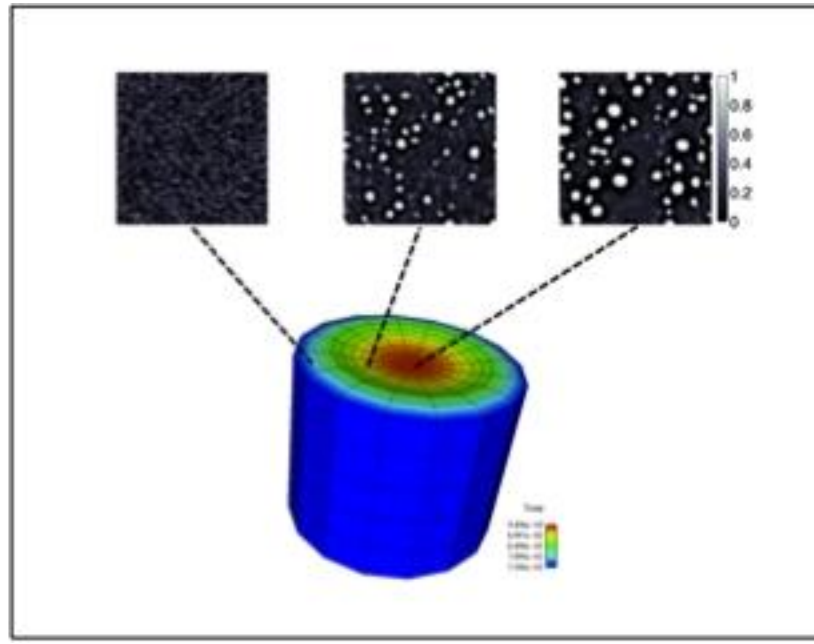
What do we need and where are we going?

Coupled experiment, theory, and modeling and simulation of nuclear fuel performance.

Microscale measurement of material thermal properties.







Computed fuel temperature distribution incorporating mesoscale modeling of vacancy concentrations.

Tonks et al., accepted for publication in Nuclear Engineering and Design (May 2010)

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Notional Advanced Fuels timeline using a science based approach

2015
Develop a framework of predictive models for fuel performance and fabrication using microstructural design of basic systems

2025
Complete validation of the design models using small-scale integral experiments

2035
Complete construction and conduct operational readiness of the fuel fabrication demonstration facility

> 2040
Demonstration Irradiation and Fuel Recycling

2010 - 2015 | *2015 - 2020* | *2020 - 2025* | *2025 - 2030* | *2030 - 2040* | *2040*

Tool development

Implementation of Tools

Validation of Tools

Fuel Design using predictive tools

Initiating Demonstration

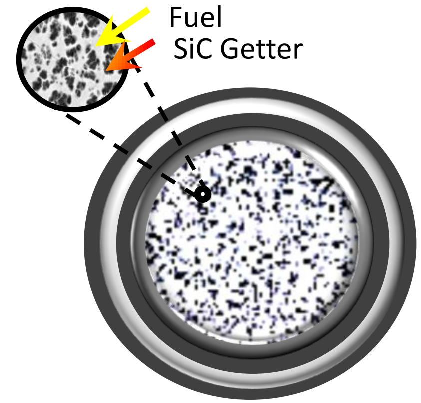
2020
Complete microstructural design of innovative fuel forms using the performance and fabrication models

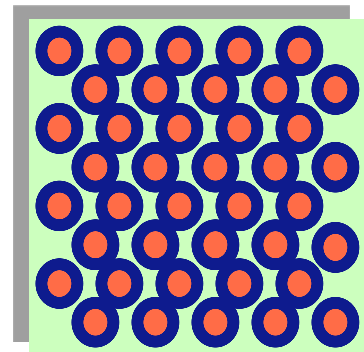
2030
Complete design of innovative fuel forms using predictive models

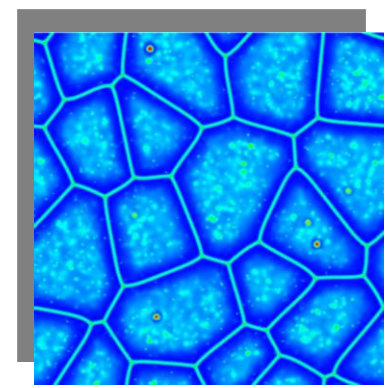
2040
Complete lead-test assembly fabrication and qualification for insertion into a prototype reactor.

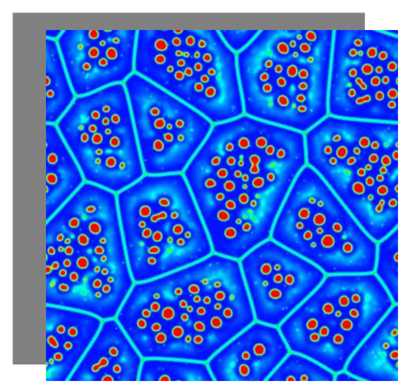
A longer-term science based approach allows us to explore innovative fuel forms (with advanced claddings)

- Accommodate different fuel cycle scenarios
- Consider longer-term, higher risk and higher payoff options.
- Chemical Forms:
    - Metal alloys
    - Ceramics
        - Oxides
        - Nitrides: N-15 issues
        - Carbides: Separations technology
- Mechanical Forms
    - Pellets (solid, annular)
    - Sphere-pac, vibro-pac
    - Dispersions (CERCER, CERMET)
    - Particle fuels (TRISO)
    - Bonding (Helium vs liquid metal)









Advanced Fuels Campaign Activities that support a science based approach

• In-pile measurements aimed at isolated phenomenology with instrumentation.

• Out-of-pile testing

• Characterization methods at micro-scale

Design of targeted in-pile and out-of-pile experiments guided by the theory and the needs of the closure models.

Design of scalable bench-scale fabrication tests with instrumentation

Micro-structural description of fuel and cladding:

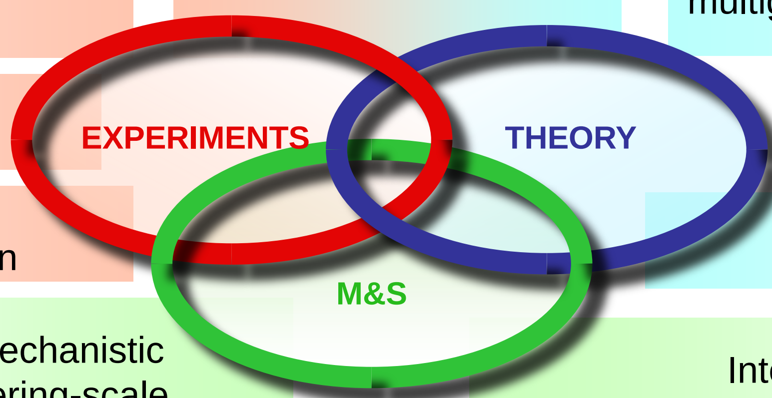
-Coupling of meso-scale theory

-Separate effect testing and properties measurement needs at sub-grain scale.

-Interpretation of results at multigrain, multi-phase scale

Detailed characterization of feedstock properties

Small-scale fabrication tests with enhanced instrumentation



Feedstock effects on the product quality

Fabrication techniques for controlling microstructure

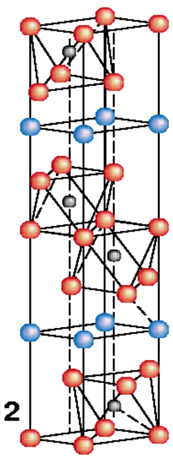
Fabrication simulator using mechanistic models to scale up to engineering-scale applications

Integral fuel-performance code to predict behavior at assembly-scale during steady-state and transient conditions.

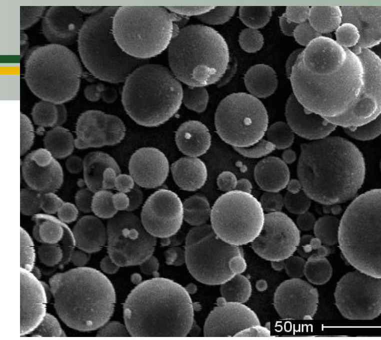
Transformational Fuel Concepts

Advanced Metallic Fuel Concept for Reliable Performance to Ultra-high Burnup
Vented Fuel Pellet/Getter Concept for High Burnup Fuel
Uranium Alloy Metal Fuel for Light Water Reactors
Dispersion Fuel
Ultra-high Burnup Metallic Inert Matrix Nuclear Fuel Concept
Advanced High Integrity Gas Cooled Fast Reactor Fuel
Multi-Layer Co-Extruded Metallic Fuel for Fast Reactors
Enhanced Thermal Conductivity and Grain Boundary Engineering for Oxide Fuels
High burn-up ceramic composite Nuclear Fuels
Thorium Fuel Development Path Forward

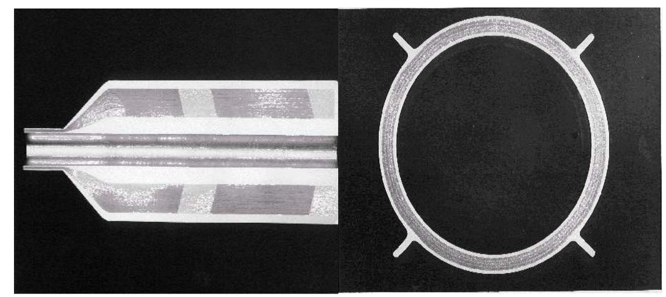
Advanced Cladding



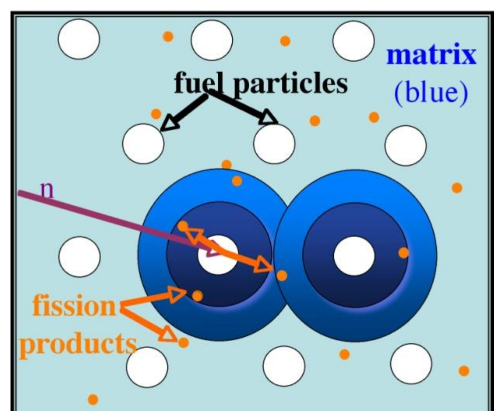
Ti_3SiC_2 Unit Cell



Microballoon powder



Co-extrusion fabrication



Phase and Microstructure Design

Summary and Conclusion

- **5 year objective is a full transition to science based approach by developing the tools necessary for such approach.**
  - Full transition to a science based approach.
  - Development of the tools necessary to predict fuel behavior and performance at the phase structure scale.
  - Develop the infrastructure necessary to study complex irradiated fuel systems at this level.

- **Long-term objective**
  - Conduct the research, development, and demonstration on the various novel fuel systems needed for the implementation of the Imperatives covered under the Nuclear Energy RD&D Roadmap.
  - Use the goal oriented science based approach to reduce the development time of critical path fuel system technology.